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The White Dwarf Deficit in Open Clusters: Dynamical Processes

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ABSTRACT

In Galactic open clusters, there is an apparent paucity of white dwarfs compared to the number expected assuming a reasonable initial mass function and that main-sequence stars with initial mass $<\sim 8\ M_\odot$ become white dwarfs. We suggest that this lack of white dwarfs is due at least in part to dynamical processes.

Non-spherically symmetric mass loss during the post-main-sequence evolution would lead to a few kms^{-1} isotropic recoil speed for the white dwarf remnant. This recoil speed can cause a substantial fraction of the white dwarfs formed in a cluster to leave the system.

We investigate this dynamical process by carrying out high-precision N-body simulations of intermediate-mass open clusters, where we apply an isotropic recoil speed to the white dwarf remnants. Our models suggest that almost all white dwarfs would be lost from the cluster if the average recoil speed exceeds twice the velocity dispersion of the cluster.

Subject headings: open clusters and associations: general — white dwarfs — methods: N-body simulations

1. Introduction

Weidemann (1977) first argued that the number of white dwarf (WD) members of the Hyades cluster was unexpectedly low. Although membership information was quite incomplete in 1977, reasonable estimates for the predicted number of initial massive stars that could have evolved into WDs suggested that approximately half the WDs were missing. The cooling time for the faintest Hyades WD was also less than half the cluster age, again pointing to missing WDs, specifically the oldest ones. Adopting an initial mass function and assuming that stars with initial main-sequence mass < 6 $M_\odot$ evolve to become WDs, Weidemann et al. (1992) quantified the Hyades WD 'deficit'. With these assumptions, 28 WDs are predicted to have been formed in the cluster. After three decades of searching, only seven WD members are known. This deficiency of WDs in young open clusters has been seen in the few other open clusters for which extensive searches for WDs have been made (e.g. Kalirai et al. 2001).

As has been recognized by all of the groups working in this area through the years, there are three obvious explanations for the missing WDs in intermediate-age clusters. First, it is possible that, in significant conflict with stellar evolution models, the critical initial mass above which stars explode as core-collapse supernovae is much less than the canonical value of $6 - 8$ $M_\odot$. The presence of the lone Pleiades WD member, LB1497, with a progenitor mass of at least 7 $M_\odot$ (Claver et al. 2001) is not consistent with this explanation. Second, because of their low luminosity, WDs are difficult to detect as members of binary systems. As demonstrated most recently by Williams (2003), with reasonable assumptions for the binary fraction and mass-ratio distribution, a significant fraction (20 - 50%) of WDs are likely to be hidden in binary systems. This is at least a part of the explanation. Finally, most open clusters are steadily losing stars due to dynamical evaporation. The possibility that WDs have been *preferentially* lost from clusters has been investigated in various ways starting with Aarseth & Woolf (1972), Wielen (1974) and Pels, Oort & Pels-Kluyver (1975) and is still a topic of active investigation today (e.g. Hurley & Shara 2003). Although there is no unanimous consensus among the studies, it is generally agreed that preferential evaporation of WDs from clusters is not a significant contributor to the observed WD deficit.

Here we consider an alternative scenario, as already proposed by Weidemann (1977), in which the paucity of WDs is due to their escape from the cluster potential as a consequence of recoil speed attained during the non-spherically-symmetric loss of their red giant envelope. The typical velocity dispersion of the Galactic open clusters is $< 2\mathrm{kms}^{-1}$ (e.g. the Hyades one-dimensional velocity dispersion is 0.3 kms^{-1}; de Bruijne, Hoogerwerf & de Zeeuw 2000). The mass of the main-sequence-turnoff stars is ~ 5 $M_\odot$ for a 100 Myr old cluster and 2 $M_\odot$ for a 1 Gyr old cluster. The typical mass of the first WD remnants is ~ 0.8 $M_\odot$ (Weidemann

2000; Claver et al. 2001). The first cluster stars to become WDs therefore lose 80% or more of their initial mass through a combination of stellar winds and planetary nebula ejections. Typical stellar wind velocities for the giant-branch phases of stars that become the first WDs in a cluster are on the order of 10 kms^{-1} (Kudritzki & Reimers, 1978) and even the 'slow', high-density planetary nebula wind is typically expanding away from the central star at 20 kms^{-1} (e.g. Kaler & Aller, 1974). Thus, even a 1% deviation from spherical symmetry in the integrated mass loss history would lead to a recoil speed of a few kms^{-1} for the first WDs formed in clusters. Spruit (1998) argues that an asymmetric mass loss fraction of the order of 10^{-3} during the AGB phase could explain the rotation period distribution of WDs. A larger asymmetric mass loss would also induce a non negligible recoil speed. Furthermore the author points out that such asymmetries can in principle be observed by proper motion studies of the clumps in interferometric images of SiO maser emission. A similar problem has been considered for neutron stars (Spruit & Phinney 1998). The recoil speed of many pulsars is observed to be greater than 100 kms^{-1} (Hansen & Phinney 1997). These large speeds are probably induced by a non-spherically-symmetric supernova explosion. Monte Carlo simulations of supernova explosions in primordial binaries show that large recoil speed leads to a substantial loss of the neutron star remnants even in rich and strongly bound globular clusters (Pfahl et al. 2002).

We consider a much less volatile situation in which the WDs are formed in an open cluster environment with a few kms^{-1} recoil speed. In §2, we briefly describe our numerical method and the formulation of the problem. The results of our numerical computation is presented in §3 and we discuss their implications in §4.

2. Numerical scheme and model parameters

We perform N-body simulations using the direct N-body code NBODY6 (Aarseth 1999). This numerical scheme enables us to follow the orbits of the stars in an open cluster with high accuracy. It is a direct summation code with block time-steps, i.e. the time-steps are quantized to powers of 2 (Makino 1991) and an Ahmad–Cohen neighbour scheme, which splits the force polynomial of a particle into an irregular part due to the neighbouring particles and a regular part of the more distant particles (Ahmad & Cohen 1973). It has a Hermite integrator which is a fourth-order predictor–corrector scheme with coordinate truncation error proportional to Δt^5 (Makino & Hut 1988). Binaries and close encounters between two stars are treated by the Kustaanheimo–Stiefel (KS) regularization method (Kustaanheimo & Stiefel 1965). Close encounters between single stars and binaries, binaries and binaries or even higher multiplicity of close particles are studied by a special method, known as chain

regularization (Mikkola & Aarseth 1993, Mikkola 1997). The code is also able to treat primordial binaries and has a scheme to implement the stellar evolution of the stars in the cluster (Hurley, Pols & Tout, 2000).

For our open cluster initial models we chose a multi-mass King model (King 1966, Michie & Bodenheimer 1963) with concentration parameter $W_0 = 5$. We perform simulations with $N_{\rm tot} = 2000$ and 10 000 particles. The tidal field is adjusted to a Galactic central distance of 10 kpc. We perform simulations with different initial binary fractions ($f_{\rm b} = 0$, 0.2, 0.4 and 0.8). The initial mass function (IMF) is taken from Kroupa, Tout & Gilmore (1993). The binary population contains only hard binaries. Most soft binaries would be disrupted by the intra-cluster forces before the first WD is formed. For primordial binaries the total mass of the binary was chosen from the Kroupa-IMF, which was not corrected for the effect of binaries, and the component masses were then assigned according to a uniform mass-ratio distribution. The orbital separation was taken from the log-normal distribution of Eggleton, Fitchett & Tout (1989) with a maximum of 100 AU and the orbital eccentricity was taken from a thermal distribution (Heggie 1975). The properties of the two open cluster models can be found in Table 1.

Our low-mass model resembles an open cluster like the Hyades, which is $7 \cdot 10^8$ years old (Perryman et al. 1998), has a tidal radius of about 9 - 14 pc and currently numbers ~ 400 stars. Most likely it had 1000 - 2500 stars initially.

As described above, we include a recoil speed if a WD is formed. If the ejection of the planetary nebula which leaves a WD behind is anisotropic at a level of only a few percent, this mass loss would result in a recoil velocity of the new WD in the order of a few kms^{-1}. Therefore we perform simulations with kick velocities randomly chosen from a Maxwellian with mean velocity $v_{\rm kick} = 1$, 2 or 5 kms^{-1}. The direction of the kick has an isotropic distribution.

3. The results of numerical simulations

In the simulation without a kick velocity almost all WDs remained in the system. They also tend to be concentrated in the cluster cores. This result can be explained by the relative high mass of the WD progenitors (Hurley & Shara 2003). N-body systems like open clusters preferentially lose low-mass stars and some of the very high-mass stars due to multiple close encounters in the centre of the system. Stars with masses similar to WDs' progenitors would be overrepresented in the cluster cores. After they lose 90% of their initial mass the WD remnants begin to diffuse to the outer regions of the cluster. However, the diffusion time

scale is longer than the two-body relaxation time scale. Consequently, these WD remnants remain relatively centrally concentrated.

However, when we include a kick acquired during evolution to the WD phase, some WDs gain enough velocity to leave the system. In the low-mass systems ($N = 2000$) a mean kick velocity of 2 kms^{-1} depletes the number of WDs significantly. In the case of high mass systems ($N = 10\,000$) a higher mean kick velocity of about 5 kms^{-1} is needed to deplete the cluster of a significant fraction of its WDs.

The results show that WDs are depleted significantly if the mean kick velocity exceeds twice the velocity dispersion of the open cluster. This may be understood in terms of the escape velocity which is also approximately twice the velocity dispersion in these systems. Hence, if the kick velocity is roughly equal to the internal velocity dispersion, the clusters lose a noticeable amount of WDs.

The binary fraction plays only a secondary role. With the caveat that our sample of simulations is small (we would need many random realisations of one set of parameters to reduce the error bars), there is no significant difference between the simulations with and without initial binaries. In principle hard binaries with high orbital velocities together with low kick velocities could inhibit WDs from leaving the cluster, but mostly the binaries leave the system as a whole. If we take into account that the progenitor of the WD is more massive than its companion which remains on the main sequence, the recoil has a comparable impact on the binary system as a whole. Again the escape velocity plays an important role here. The dividing line between hard and soft binaries is defined as the orbital velocity of the binary being equal to the escape velocity from the cluster. Therefore only kick velocities higher than the escape velocity of the system are able to break up such binaries.

Table 2 shows the results of our simulations taken at 100 Myr. Some WDs have formed and this is also approximately one relaxation time of the clusters. To show the time evolution of these results we followed certain calculations to 500 Myr and some up to 1 Gyr. This time evolution is shown in Fig. 1 for the $N = 2000$ cases and in Fig. 2 for the $N = 10\,000$ cases. In each plot two lines are shown. The dotted line is the evolution of the total number of stars in the system. The solid line shows how many of the produced WDs are still in the system. If there is no kick velocity the line of the WD fraction is above the line of all stars as expected. Including the kick velocity and increasing it moves the line of the WDs downwards and as soon as the mean kick velocity exceeds the escape velocity of the cluster the fraction of WDs is significantly lower than the fraction of stars remaining in the system. This means there is a significant WD deficit in these systems.

The remaining WDs are mainly in binaries and preferentially close to the centre of the

cluster in the simulations with low kick velocities, and more likely to be found as single stars in calculations with high kick velocity.

4. Summary and Discussion

With our direct N-body simulations we have shown that if the rapid mass loss involved in the formation of a WD progenitor is asymmetrical at a level of one or a few percent, the newly-formed WD suffers a recoil kick which is able to deplete an open cluster of almost all of its WDs. From energy arguments, this recoil velocity is at least of the order of a few kms^{-1}. But this is already enough to exceed the escape velocity, i.e. to deplete a low mass open cluster of almost all its WDs. More massive open clusters are able to retain WDs within the cluster but still show a significant depletion of WDs.

The best studied intermediate-age open clusters in the Milky Way exhibit a deficit of WDs, even after correcting for WDs hidden in binaries. Our results are in agreement with the data compilation of von Hippel (1998). The open clusters studied by von Hippel exhibit a steep IMF slope of -2.35 to -3. We suggest that this deficiency can be explained via the combined process of small kicks imparted during the mass loss history and subsequent evaporation from the cluster. These processes act preferentially to deplete clusters of the first WDs to form and could mimic a steep IMF-slope. These stars suffer the largest amount of mass loss and statistically have the largest kicks and have spent the longest amount of time (among the WD population) as relatively low mass stars. This preferential loss of the first-formed WDs may need to be accounted for when using WD cooling times to estimate cluster ages or when tracing cluster WDs back to the main-sequence and attempting to determine the critical main-sequence mass at which WDs first begin to form.

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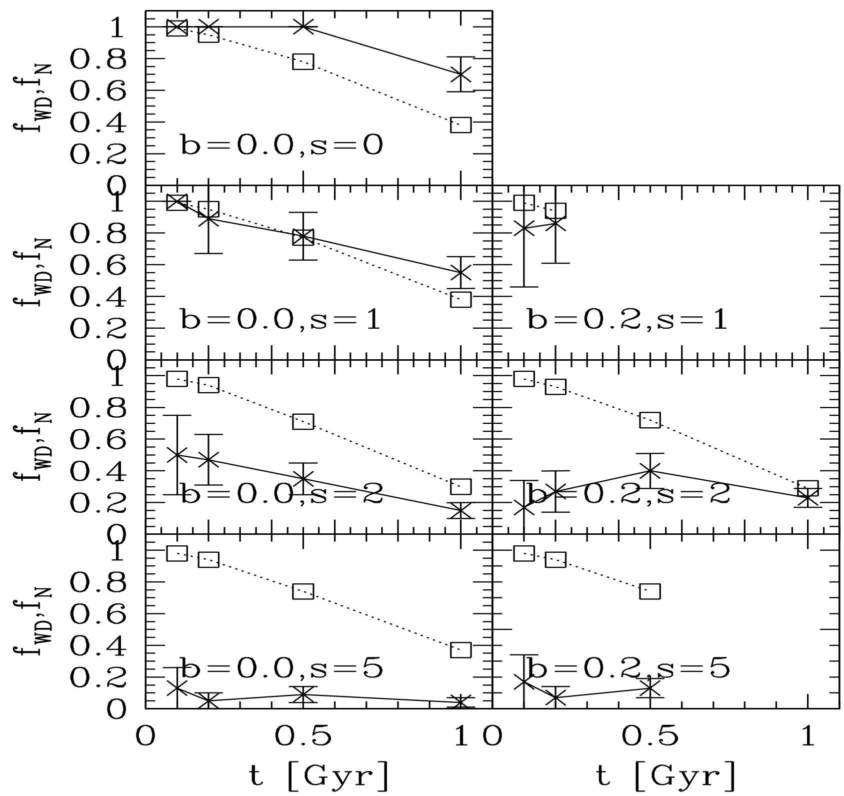

Fig. 1.— Time evolution of the $N = 2000$ calculations. Left: simulations with no initial binaries; Right: simulations with an initial binary fraction (b) of 0.2. From top to bottom the simulations with no kick velocity (s) and with mean kick velocity of 1.0, 2.0 and 5.0 kms^{-1} are shown. Crosses with error bars and solid lines show the fraction of WDs remaining in the system relative to the number of WDs produced in the system ($\mathrm{f_{WD}}$). Open squares and dotted lines show the number of stars left in the system divided by the initial number of stars ($\mathrm{f_N}$).

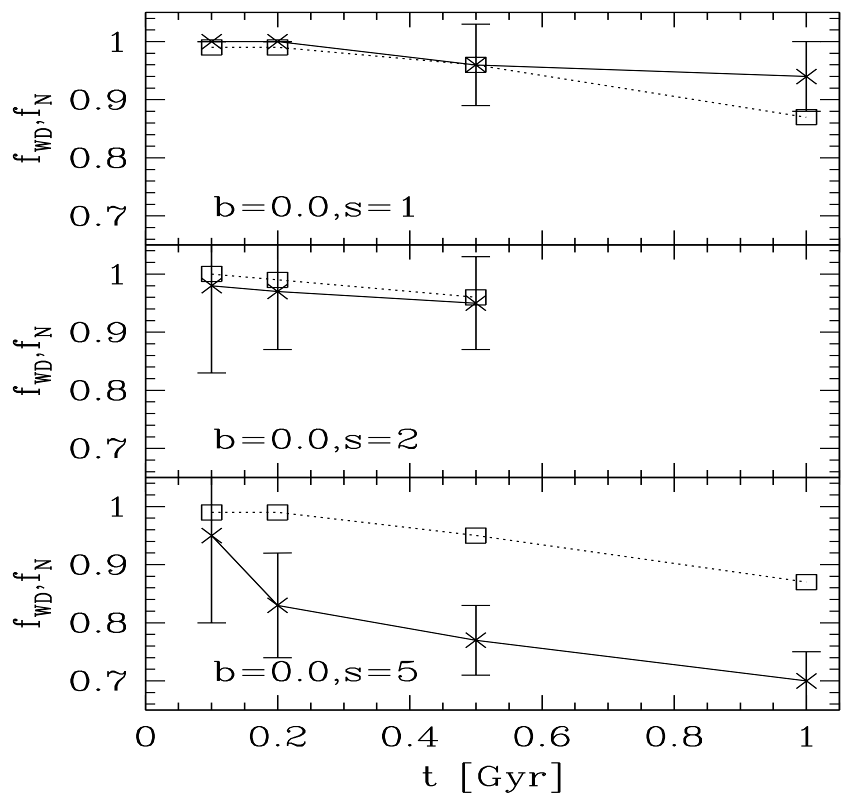

Fig. 2.— Time evolution of the $N = 10\,000$ calculations with no initial binaries (b). From top to bottom the simulations with mean kick velocity (s) of 1.0, 2.0 and 5.0 kms^{-1} are shown. Crosses with error bars and solid lines show the fraction of WDs remaining in the system relative to the number of WDs produced in the system (f_{WD}). Open squares and dotted lines show the number of stars left in the system divided by the initial number of stars (f_N).

Table 1: Properties of the open cluster models. From top to bottom: total mass, crossing time, relaxation time, tidal radius, half mass radius, core radius, velocity dispersion.

N		2000	10000
$M_{\rm tot}$	$[{\rm M}_\odot]$	1317.1	6668.1
$T_{\rm cr}$	[Myr]	6.2	2.7
$T_{\rm relax}$	[Myr]	180.7	109.1
$r_{\rm tidal}$	[pc]	15.6	26.7
$r_{\rm h}$	[pc]	2.5	2.4
$r_{\rm core}$	[pc]	0.9	1.0
σ	$[{\rm kms}^{-1}]$	0.8	1.8

Table 2: Results of our simulations after 100 Myr of evolution. The columns are the number of stars initially, the initial binary fraction, mean velocity of the kick in kms^{-1}, the number of WDs formed in the cluster, the number of WDs remaining in the cluster, the fraction of WDs remaining and the fraction of total stars remaining in the cluster. Because of the small numbers in the $N = 2000$ simulations, we performed several runs with the same parameters but different random realisations. The absolute numbers given in the table represent the first run of each set, the fractions are the statistical mean out of all simulations for a certain parameter set. The last column gives the number of random realisations performed with this parameter setting.

N	f_b	v_kick	$\mathrm{WD_{tot}}$	$\mathrm{WD_r}$	f_WD	f_N	#run
2000	0.0	0	8	8	1.00	0.99	1
2000	0.0	1	8	8	1.00	0.99	1
2000	0.0	2	8	4	0.50	0.98	1
2000	0.0	5	8	1	0.13	0.98	1
2000	0.2	1	6	5	0.83	0.98	3
2000	0.2	2	6	1	0.17	0.98	1
2000	0.2	5	6	1	0.09	0.98	2
2000	0.4	1	5	5	1.00	0.98	3
2000	0.4	2	5	4	0.80	0.98	3
2000	0.4	5	5	1	0.20	0.98	1
2000	0.8	1	3	3	1.00	0.98	1
2000	0.8	2	3	3	1.00	0.99	1
2000	0.8	5	1	0	0.00	0.97	1
10000	0.0	1	43	43	1.00	1.00	2
10000	0.0	2	43	42	0.98	1.00	1
10000	0.0	5	43	38	0.88	0.99	2
10000	0.2	2	39	38	0.97	0.99	1
10000	0.2	5	39	37	0.95	0.99	1
10000	0.4	2	27	27	1.00	0.99	1